

CEA studies on Halo formation

Nicolas Pichoff¹, Gérard Haouat¹,
Jean-Michel Lagniel¹, P-Y Beauvais²,
Didier Uriot², Romuald Duperrier²

¹ CEA/DIF-Bruyères-le-Châtel

² CEA/DSM-Saclay

History - Why Halo studies at CEA ?

Driven by projects :

- 1992-1998 : TRISPAL (Tritium production)
 - 40 mA, 600 MeV, CW, p^+
- 1998-1999 : ASH (Hybrid reactor)
 - 20 mA, 500 MeV, CW , p^+
- 1999-2001 : CONCERT (Multipurpose)
 - 100 mA, 1 GeV, 30% DC , p^+/H^-
- 2001-2002 : ESS (Spallation source)
 - 100 mA, 1.3 GeV, 10% DC , p^+/H^-
- 2003-... : SPIRAL2 (Spallation source)
 - 5 mA, 40 MeV, CW , D^+ /heavy ions

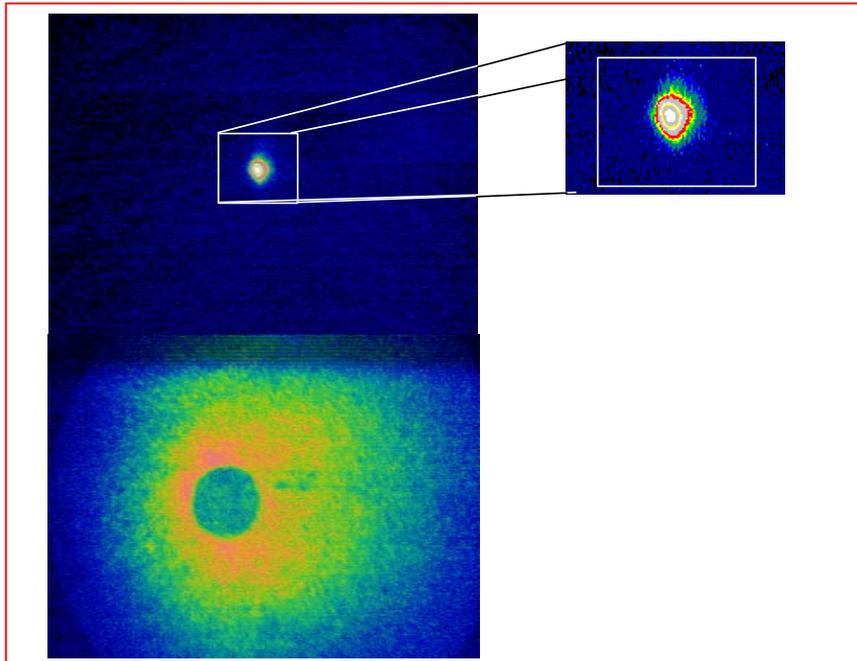
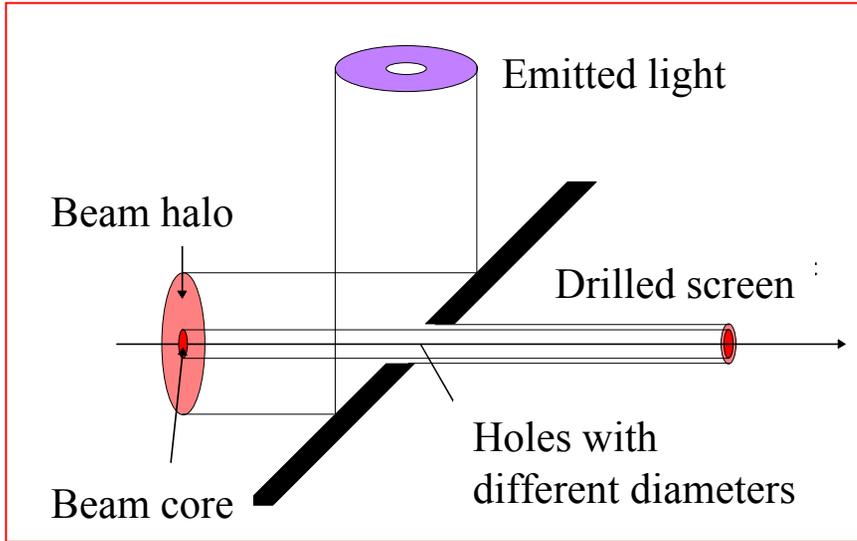


Phenomenons studied at CEA

- Experimental studies
 - ▣ ELSA – High dynamics measurements
 - ▣ FODO Channel
- Theoretical studies
 - ▣ Parametric resonances
 - ▣ Equilibrium studies
 - ▣ Scattering on Residual gas
 - ▣ Intrabeam scattering
 - ▣ Coupling resonances
 - ▣ Space-charge compensation
 - ▣ H⁻ Charge exchange with residual gas
 - ▣ Loss probability from error studies



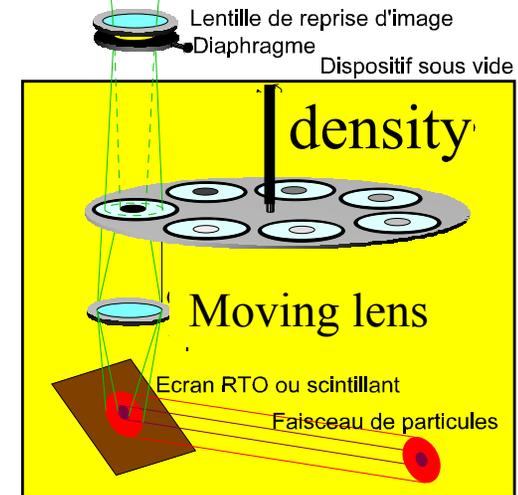
ELSA – High dynamic measurements



Intensified
CCD camera



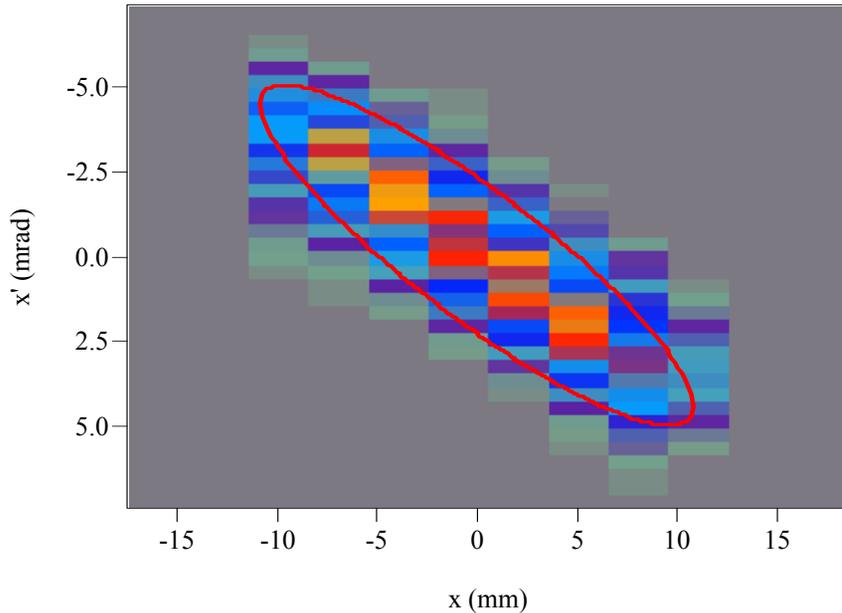
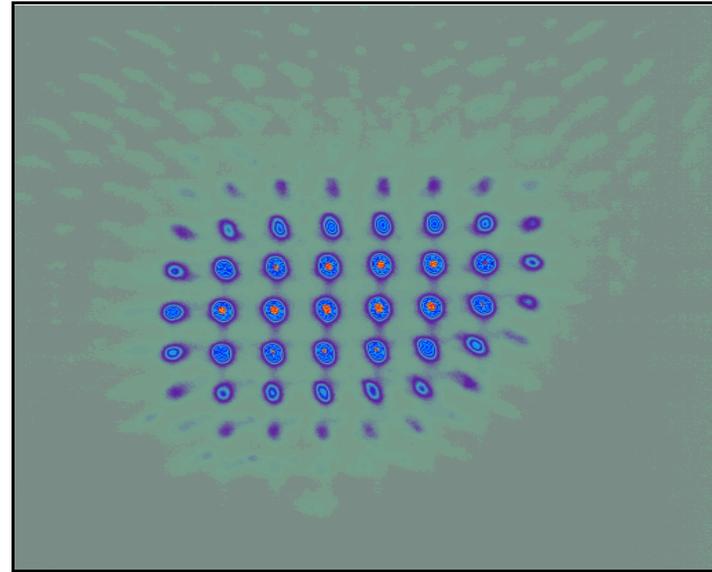
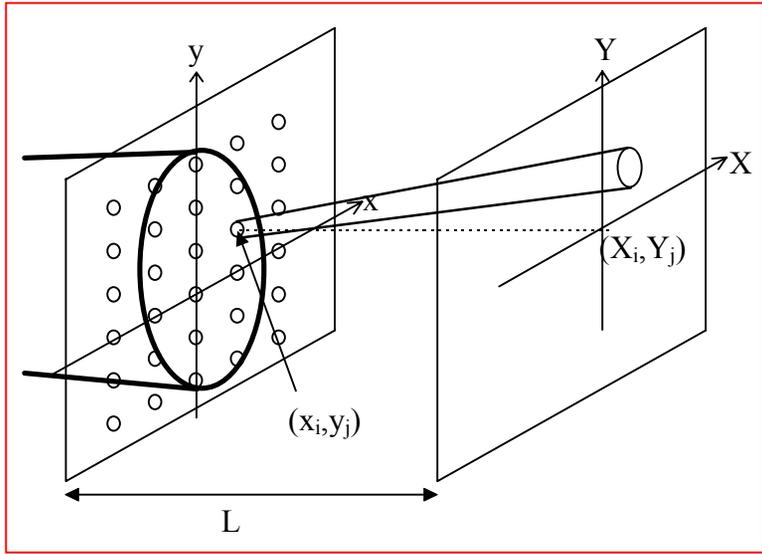
Commande, saisie et traitement
sous LabVIEW



6 to 7 decades dynamic range



FODO channel – Pepper-pot



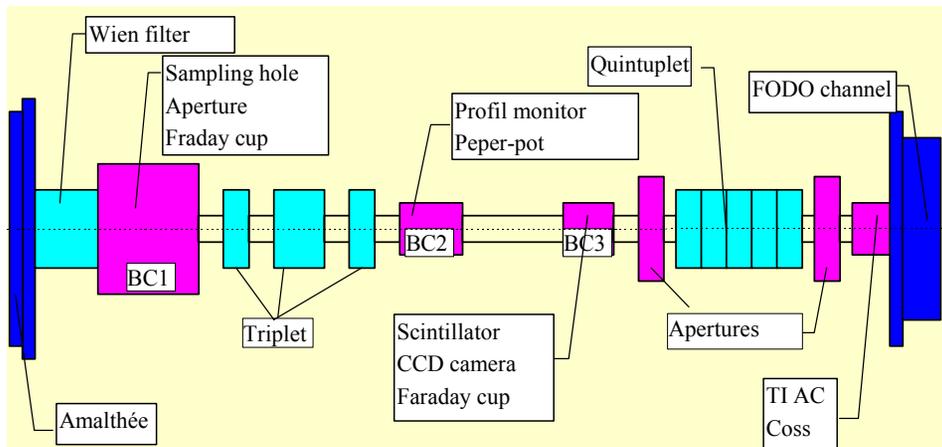
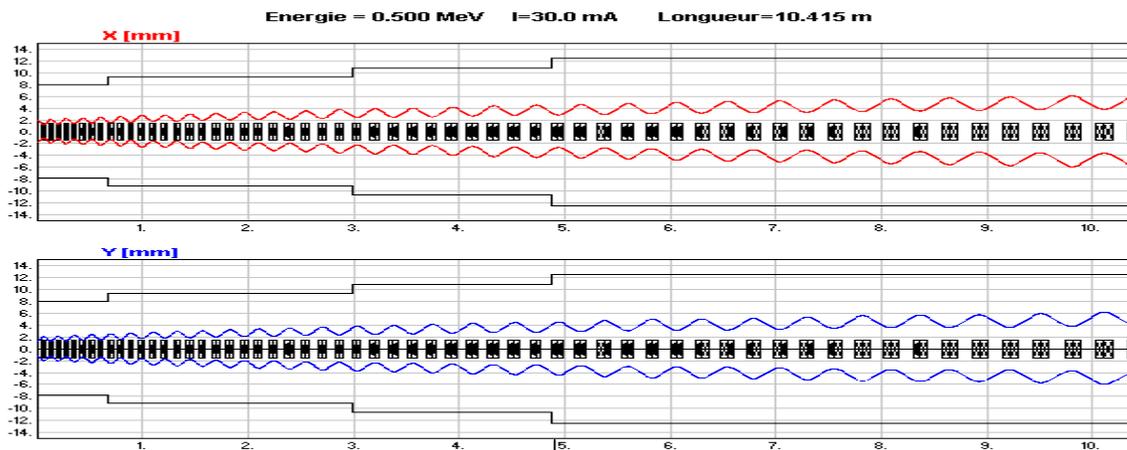
A low-resolution phase-space measurement in 1 shot



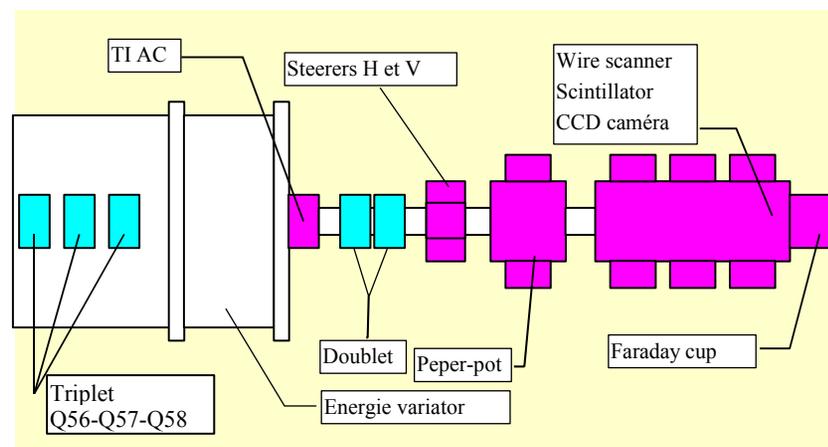
FODO channel – Experimental setup

A FODO channel with 58 quadrupoles

Protons, 500 keV, up to 50 mA, 400 μ s pulse



Before the FODO channel

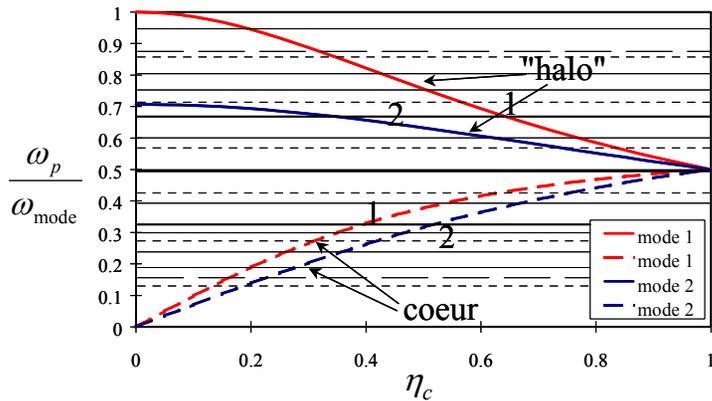


After the FODO channel



Parametric resonance

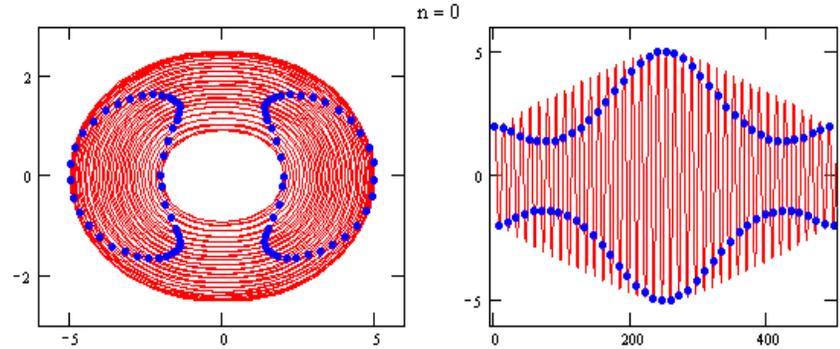
J-M Lagniel : Half integer resonance is always excited by mismatch
 Chaotic motion from resonance overlapping



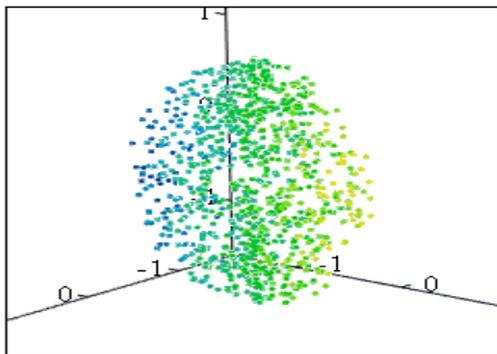
ω_0 : particle
 oscillation frequency
 without space charge

ω_p : particle
 oscillation frequency

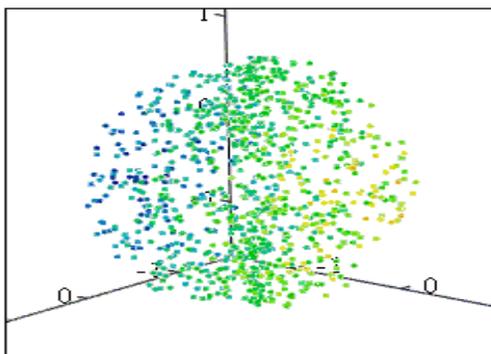
$$\eta_c \cdot \omega_0 < \omega_p < \omega_0$$



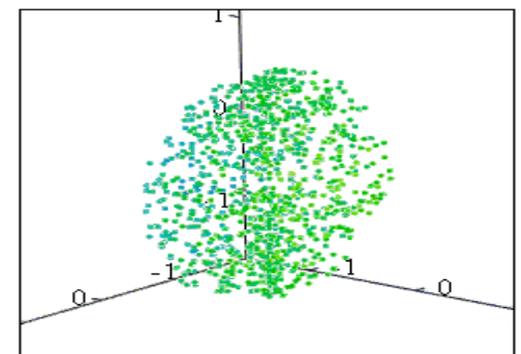
N. Pichoff - Calculation of the 3 mismatch modes in 3D



Quadrupole mode



High frequency
 breathing mode

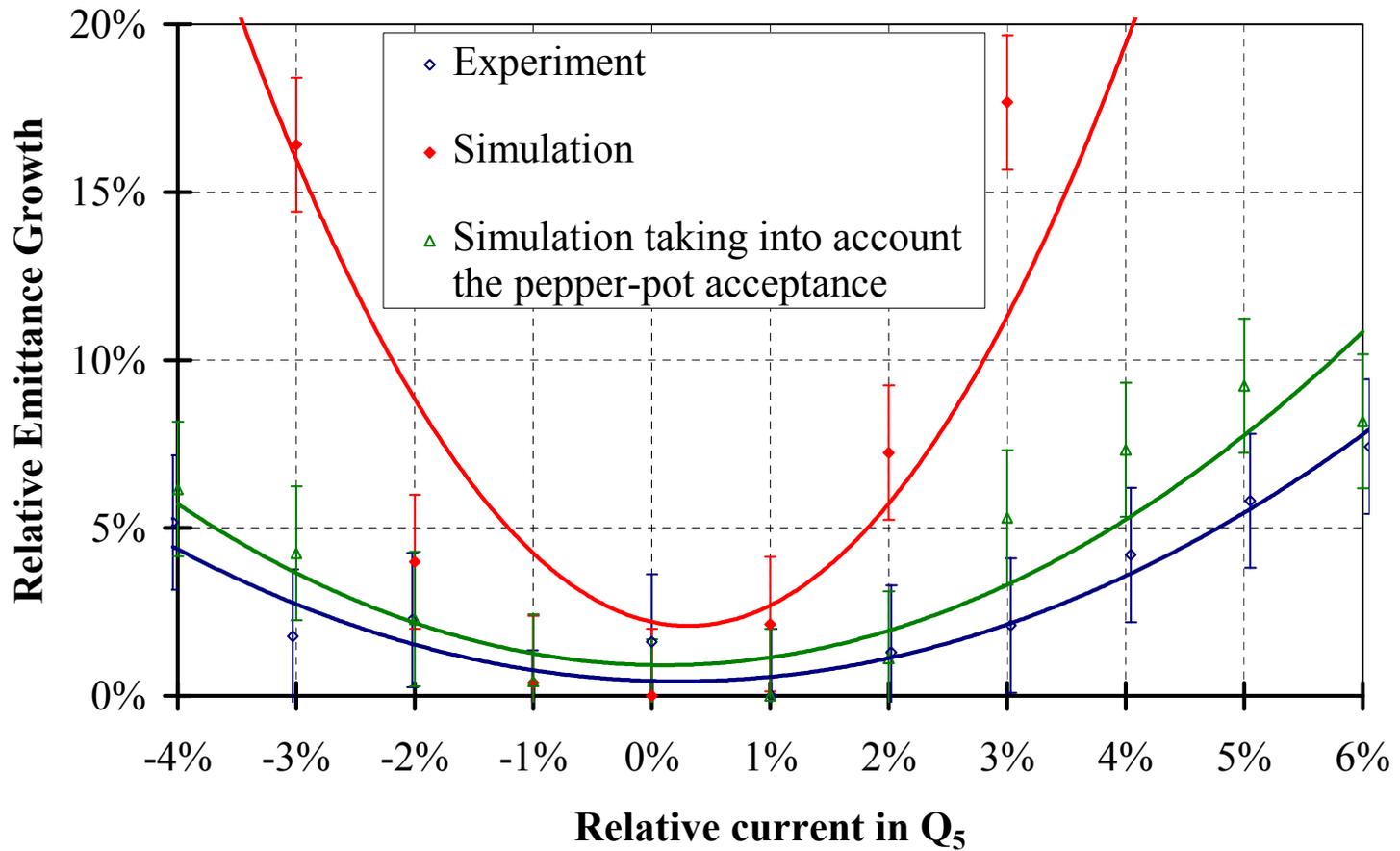


Low frequency
 breathing mode



Effect of mismatching

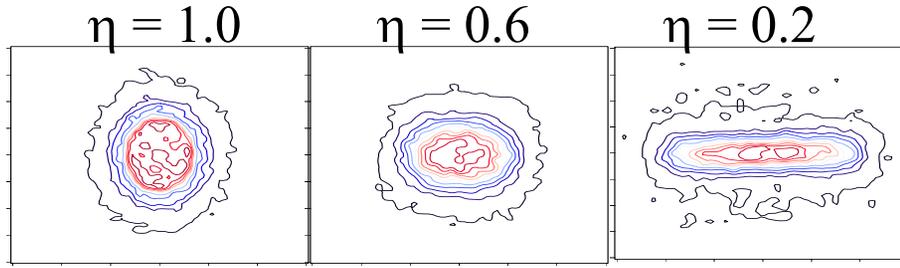
Measurement of space charge-dynamics effects in a FODO channel,
N. Pichoff et al., EPAC98



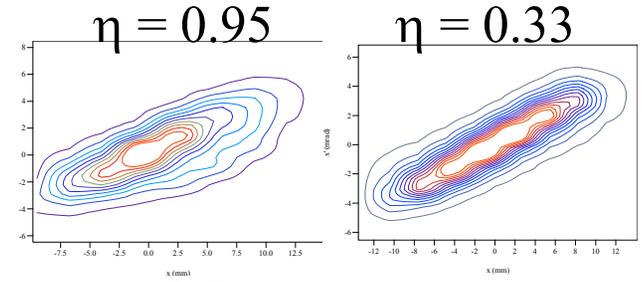
Equilibrium studies – Phase-space distrib.

For low space-charge tune depression

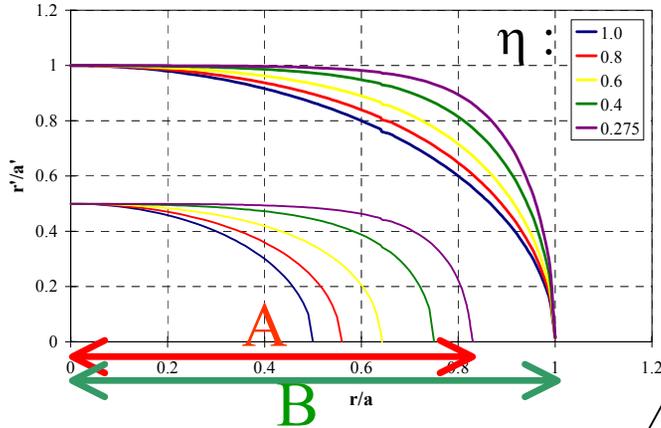
- particle (x, x') phase-space trajectories become rectangular



Multiparticle simulations

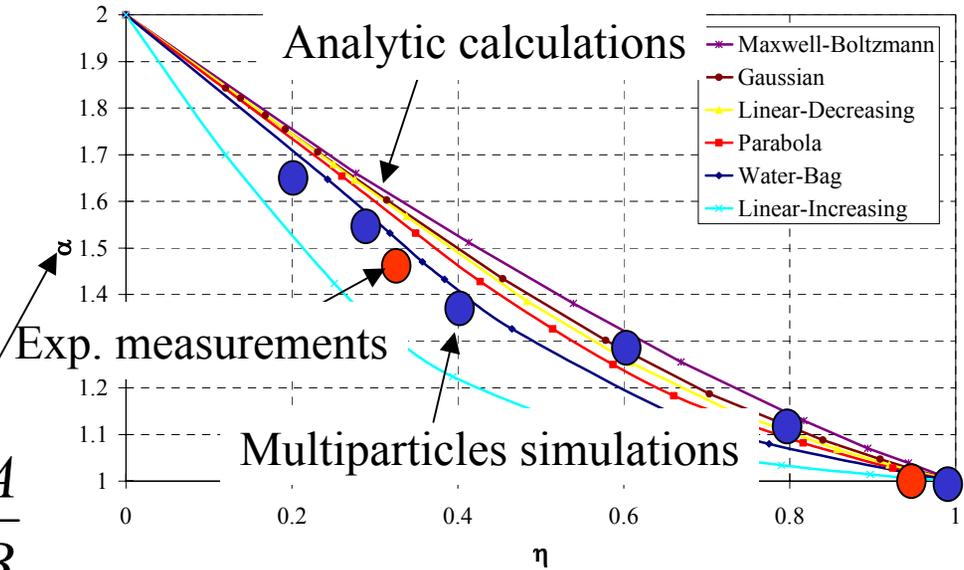


Measurement



Particle trajectories in phase-space

$$\alpha = 2 \cdot \frac{A}{B}$$



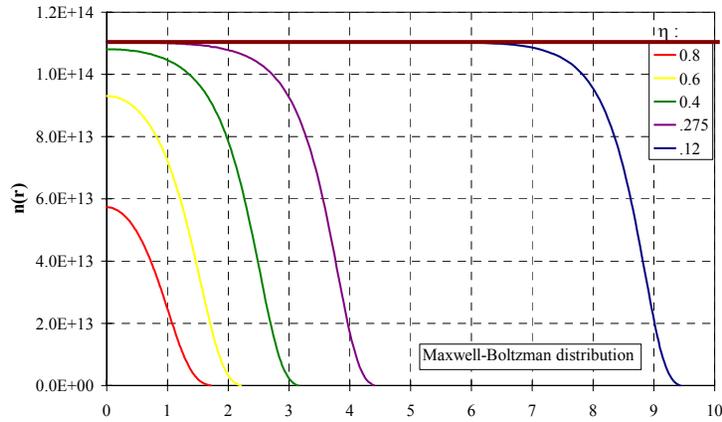
Exp. measurements

Multiparticles simulations

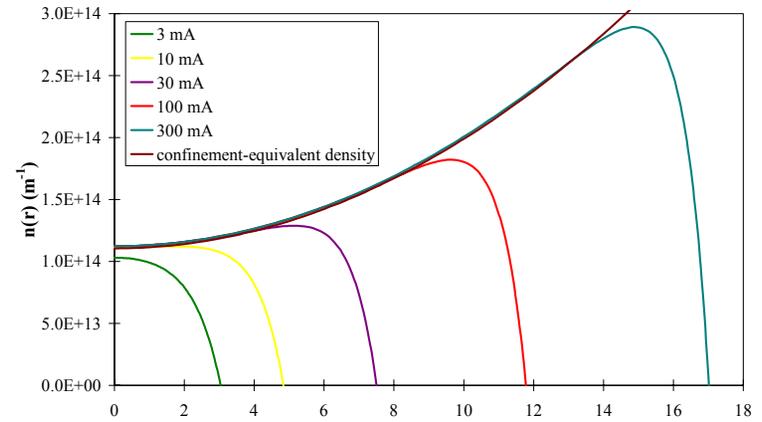


Equilibrium studies – Beam profile

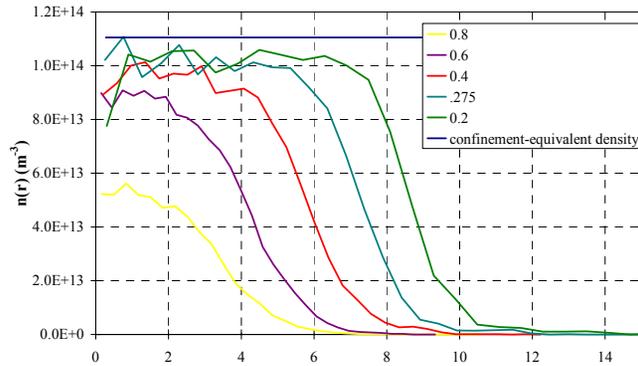
The external force can be seen as a opposite charge distribution.
For low space-charge tune depression, beam profile tends to compensate this charge distribution



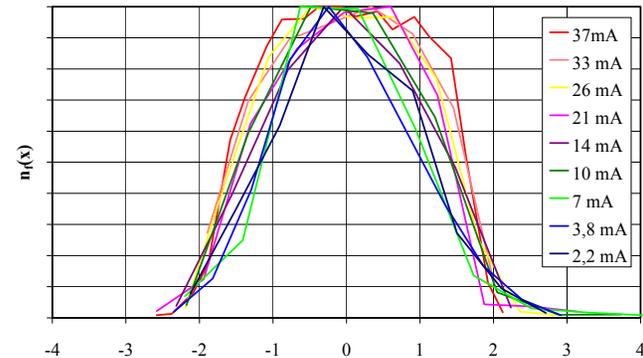
In linear force



In non-linear force



Particle simulations

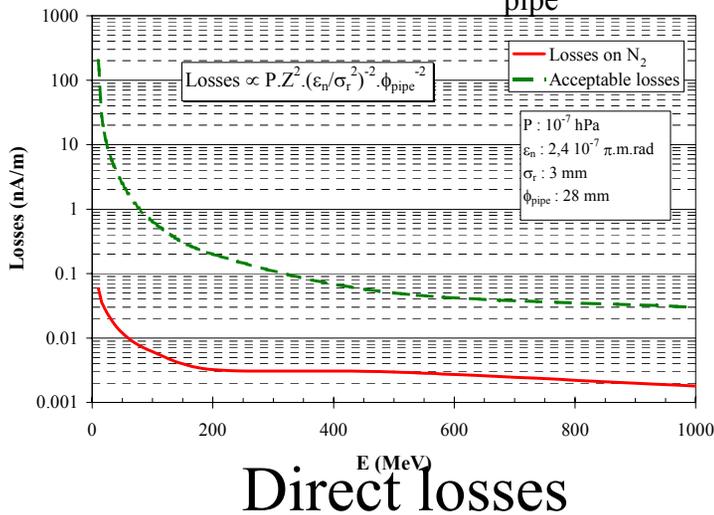
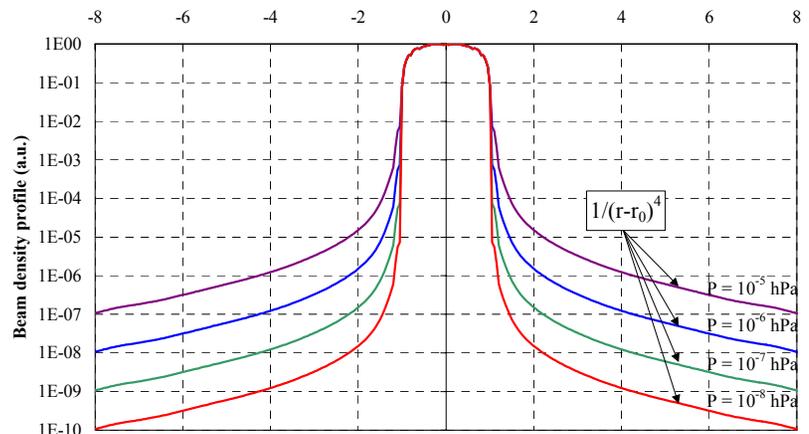
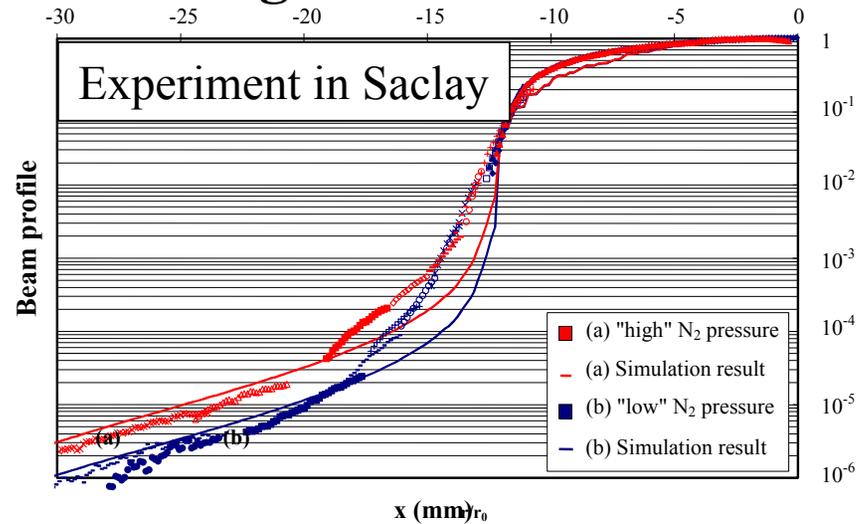
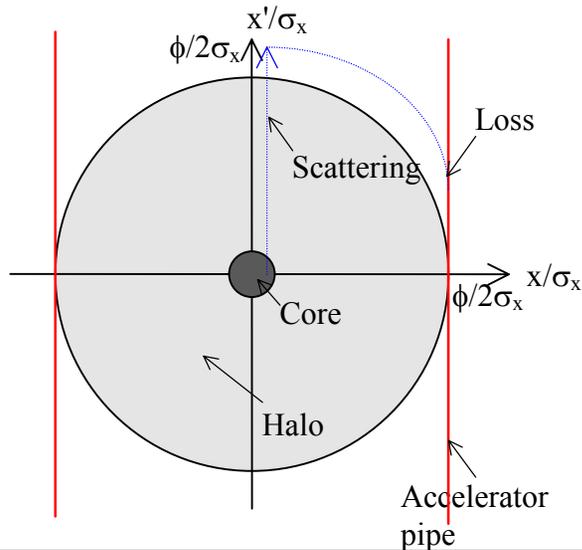


Exp. measurements



Elastic scattering on residual gas

Transverse momentum can be given to a particle through a collision on one molecule of the residual gas

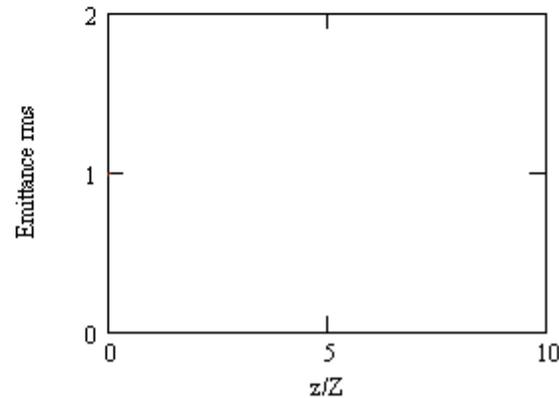
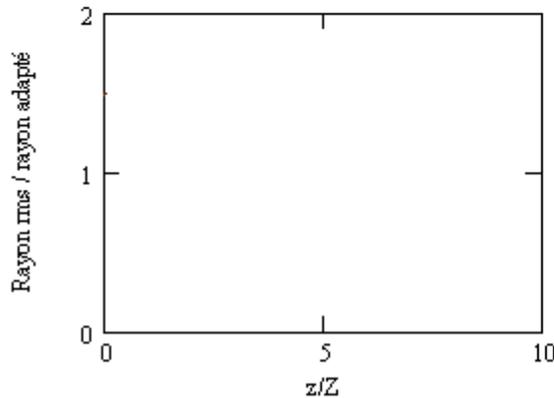
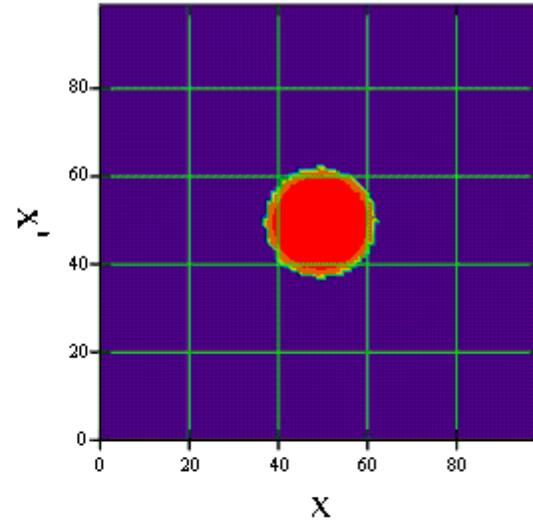
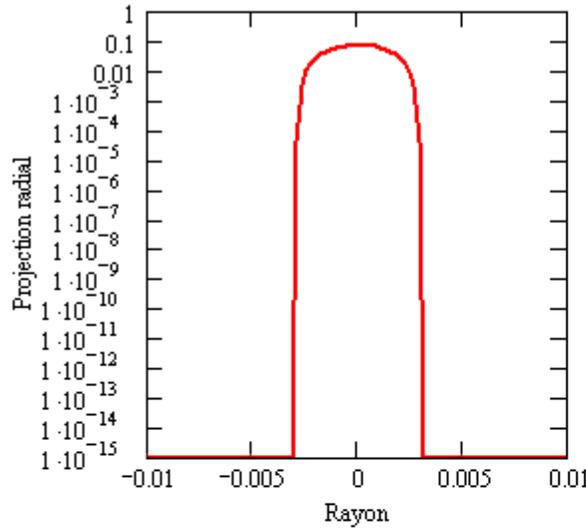


Beam tails and halo

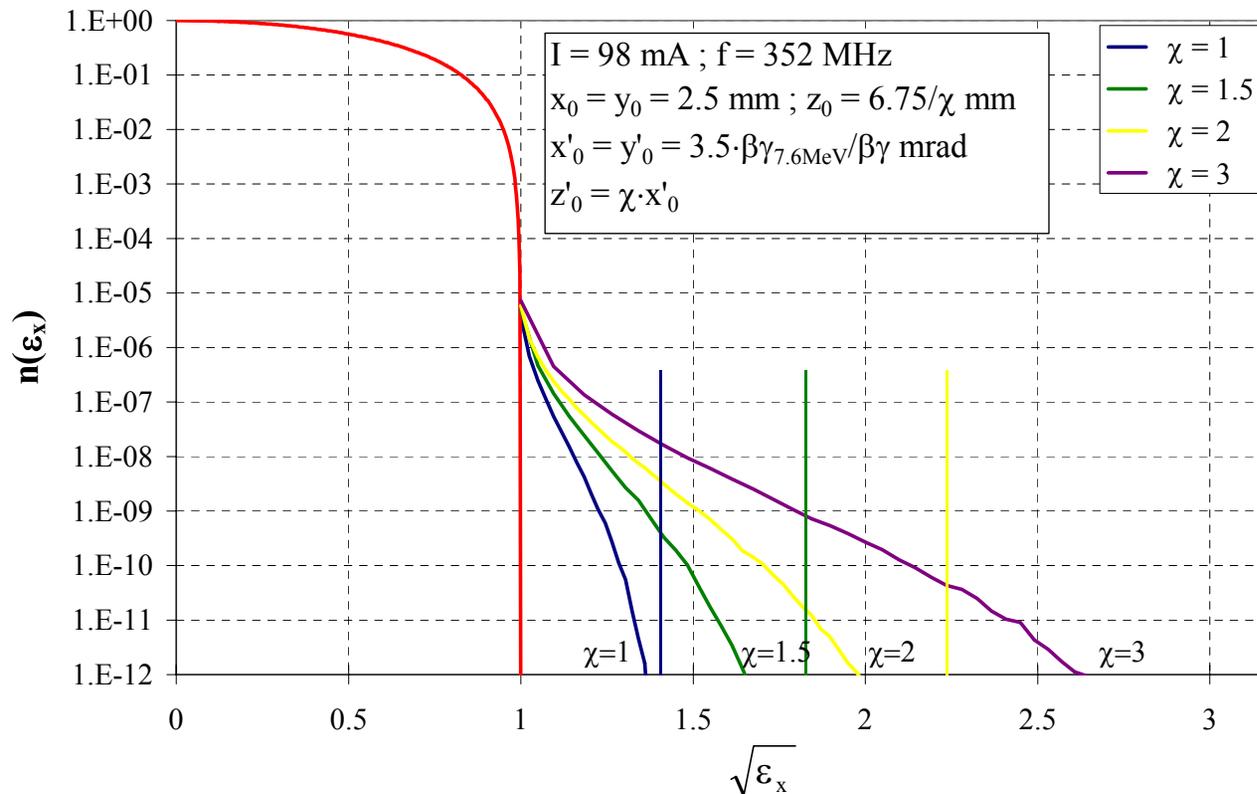
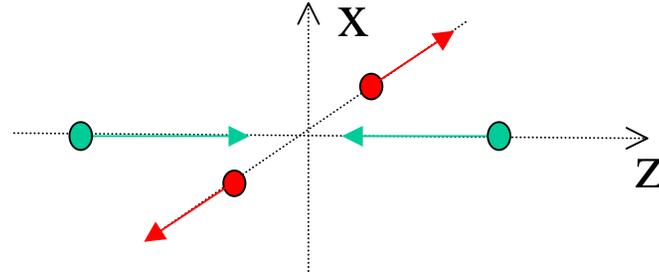


Elastic scattering on residual gas (movie)

Animation with the newest generation of CEA multiparticle codes able to reach beam profile over 10 decades.



Intrabeam scattering



χ : Ratio between the longitudinale energy and the transverse one

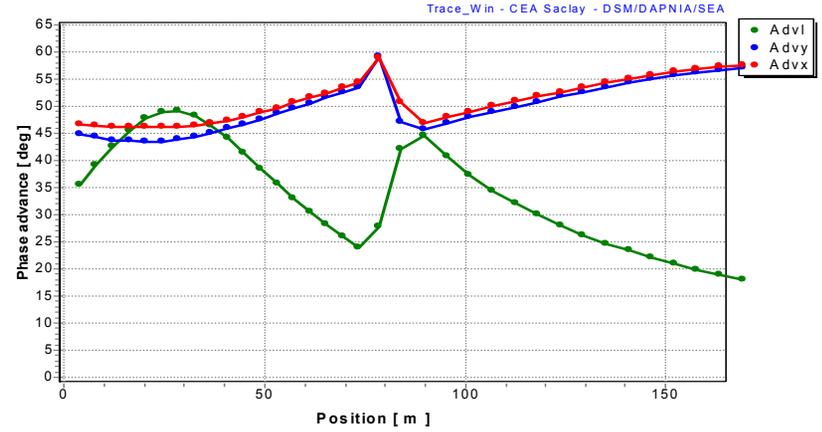
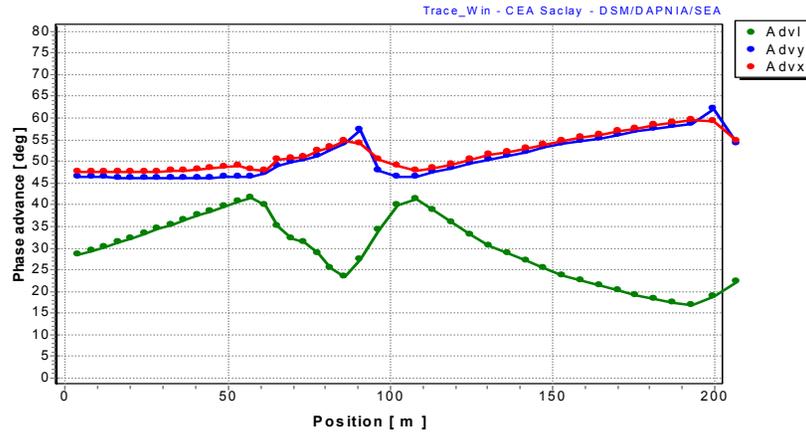
Tails from 2-body collisions



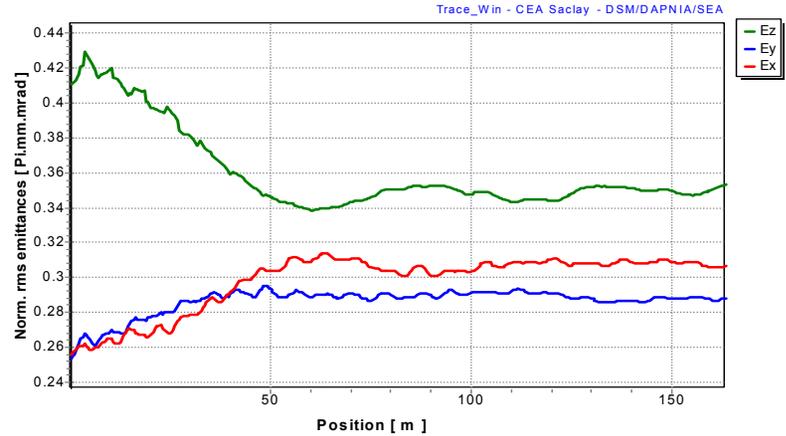
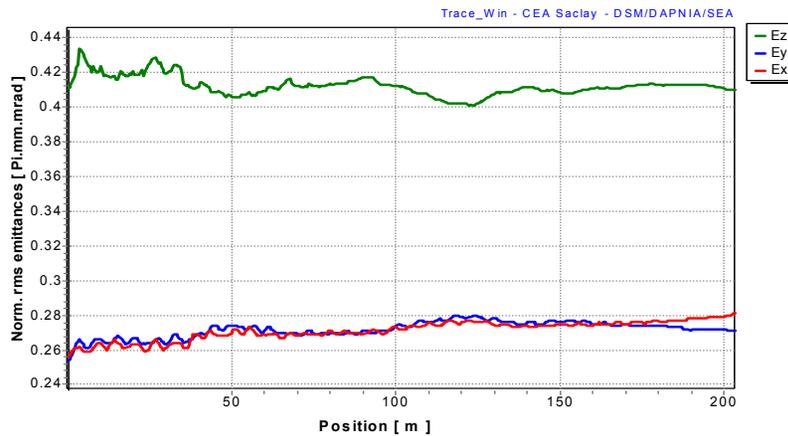
Emittance exchange

Phenomenon observed in 1999 for ASH project

Phase advances



Emittances



No phase advance crossing

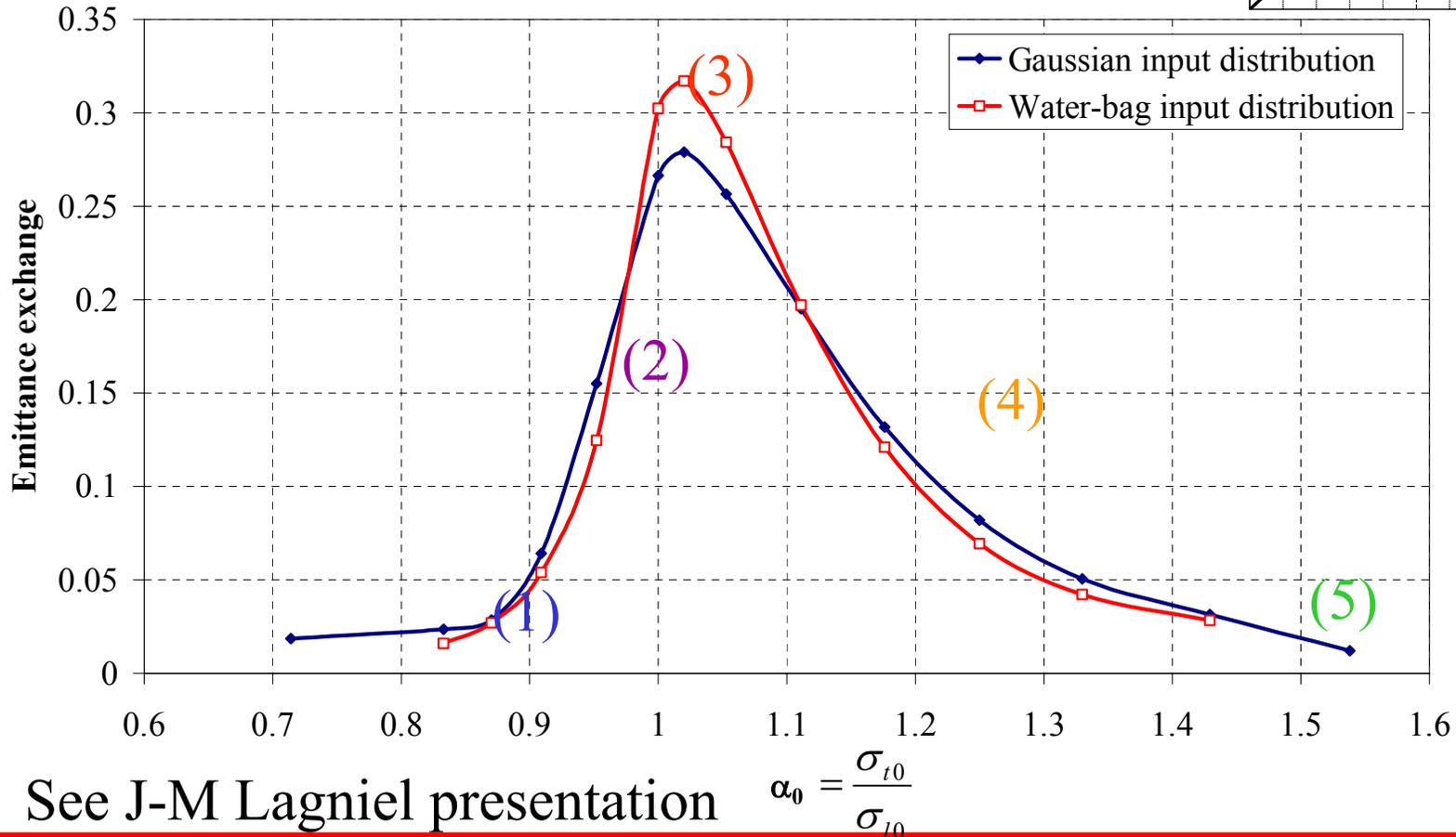
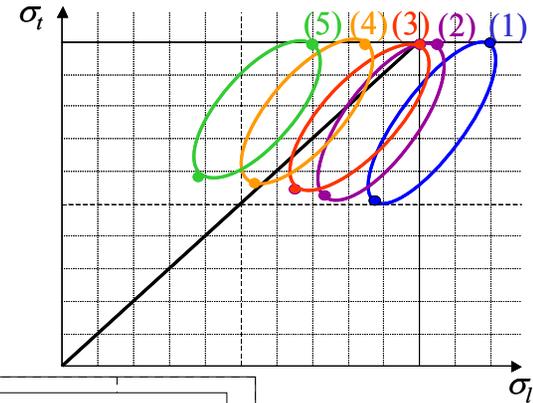
Phase advance crossing



Coupling resonance

Emittance exchange :
$$\frac{\Delta \varepsilon_l - 2 \cdot \Delta \varepsilon_t}{\varepsilon_{l0} + 2 \cdot \varepsilon_{t0}}$$

$\frac{\varepsilon_{l0}}{\varepsilon_{t0}} = 2 \quad \sigma_{t0} = 1$ For $\sigma_{l0} = 1, \eta_t = 0.53, \eta_l = 0.68.$



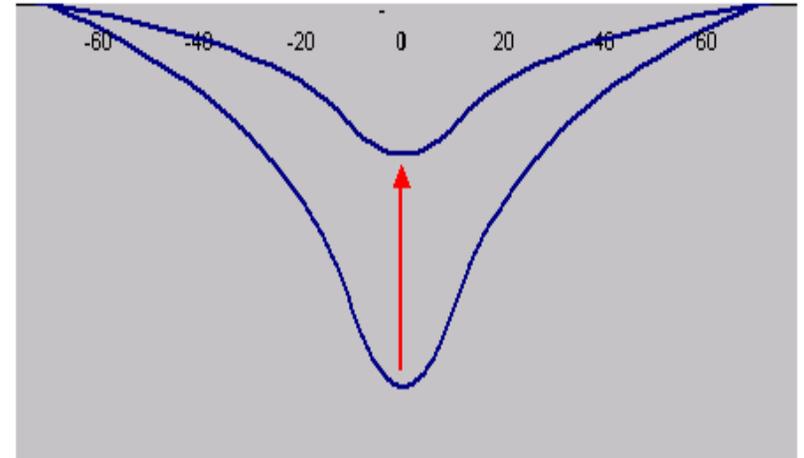
See J-M Lagniel presentation

$$\alpha_0 = \frac{\sigma_{t0}}{\sigma_{l0}}$$



Space-charge compensation

- The charge density produces a potential well in a beam, defocusing its particle.
- The beam ionises the residual gas, creating ions and electrons
- Species with opposite charge are trapped in the well, the others are expelled
- The potential well is filled
- The space-charge force is changed with time
- The matching conditions are changed with time



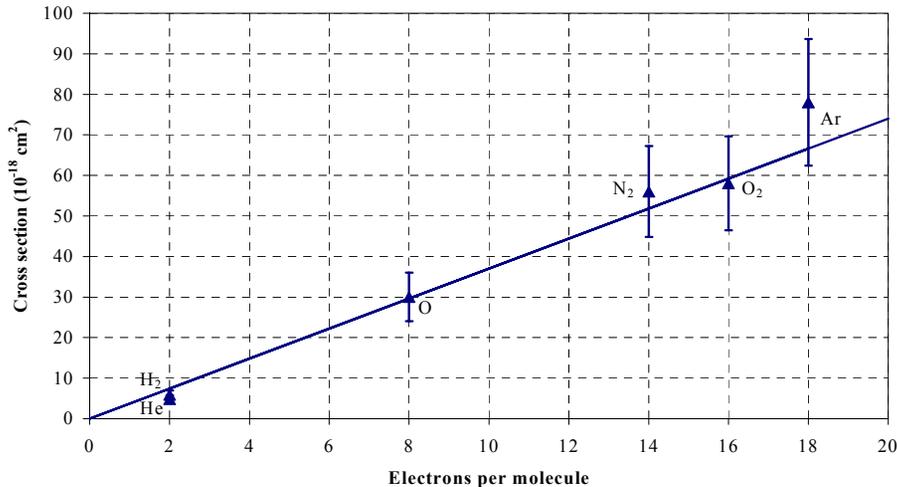
➤ **Pulse front end is mismatched**

PHDs X. Fleury (mathematics), A. Ben Ismail (beam physics)



Charge exchange with residual gas

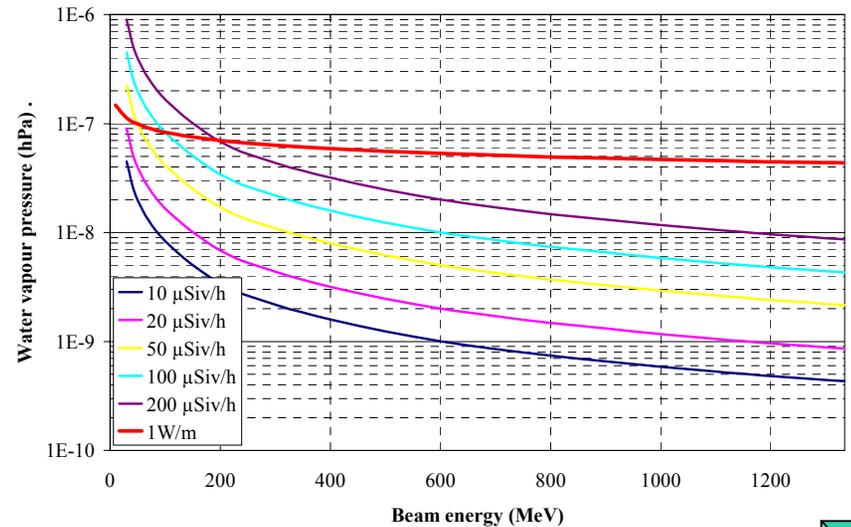
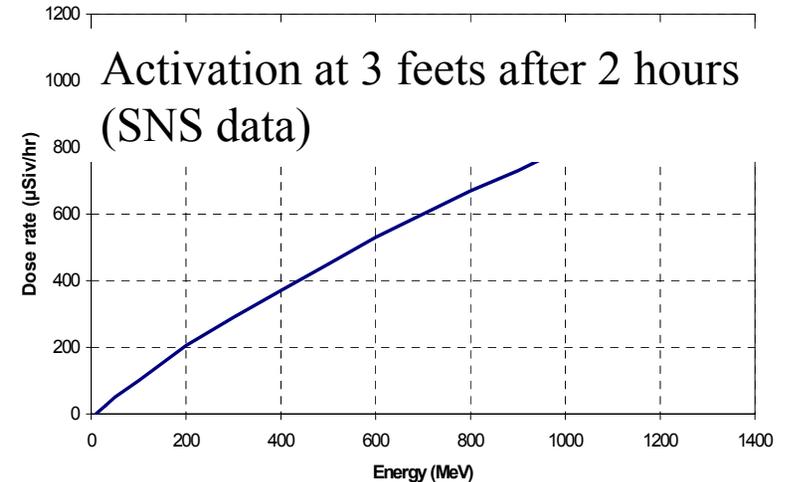
In ESS, some H^- can be neutralised by an electron exchange with the residual gas, inducing losses



Cross section of H^- stripping at 10 MeV

$$\sigma = 2.1 \cdot 10^{-20} \cdot E^{-3/4}$$

σ the cross section in m^2 ,
 E the particle energy in MeV



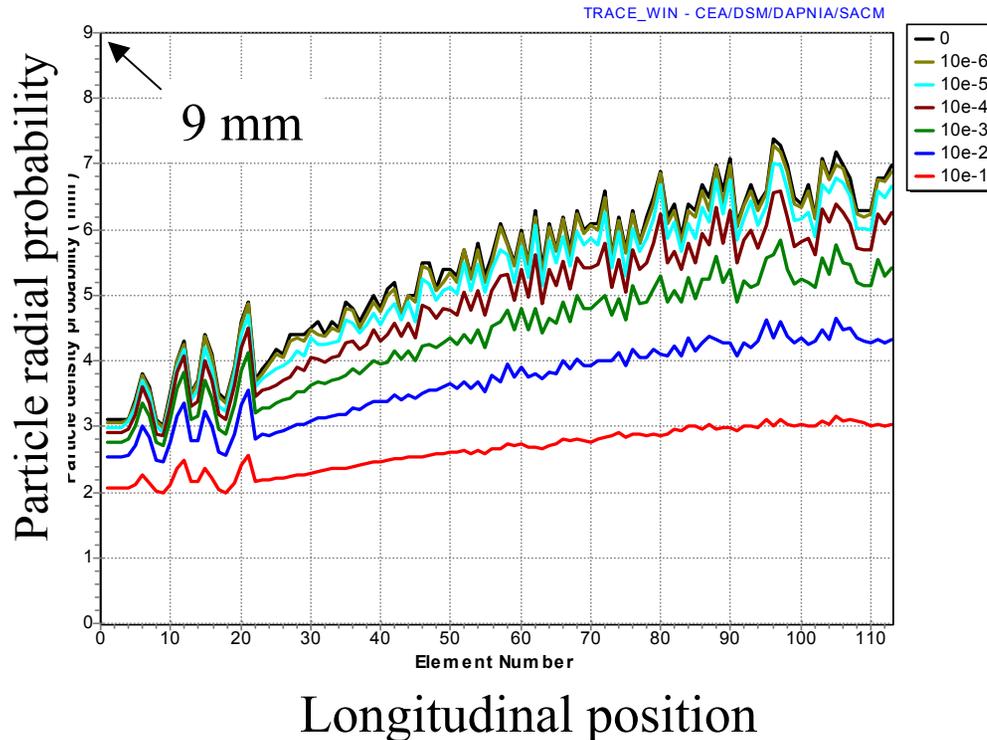
H_2O maximum pressure



Loss probability from error studies

The linac errors have an influence on beam centre of gravity displacement, mismatching and non linear forces.

- Static errors : can be measured and corrected
- Dynamic error : cannot be corrected



Statistical treatment :
 n_l linacs of n_p particles
 \Rightarrow Calculus of a
probability of presence

Applied to IPHI, IFMIF,
ESS, SPIRAL2



Selection of publications

- PAC95: G. Haouat et al., *Halo of a high brightness electron beam*.
- EPAC98: N. Pichoff et al., *Measurement of space-charge dynamics effects in a FODO channel*.
- N.I.M.A: J-M. Lagniel, *On Halo formation from space-charge dominated beams*, 345, 1994.
- DAPNIA/SEA 98/44.: N. Pichoff , *Envelope Modes of a Mismatched Bunched Beam*.
- APAC98: N. Pichoff et al., *Transverse profile equilibrium in a space-charge dominated beam*.
- Particles accelerators: N. Pichoff et al., *Halo from Coulomb Scattering of beam particles on residual gas*, vol.63, 2000
- PAC99: N. Pichoff, *Intrabeam scattering on Halo formation*.
- ESS notes, DAPNIA notes ...